Active Pre-Alignment of the CLIC Supporting System Using Closed Loop Control as a Solution for Mechanical Component's Nonlinearities and Assembly Inaccuracies

Introduction

The most critical CLIC RF components need to be pre-aligned within 14 µm rms with respect to a straight reference line along a sliding window of 200 m.

A system based on supporting structures (girders and cradles) connected in "snake"-type configuration and equipped with linear actuators is being tested. A special test mock-up was built at CERN to demonstrate, inter alia, the feasibility of remote active pre-alignment within tight tolerances. To achieve the requirements, all main parts of the CLIC mock-up were machined with high precision and measured to determine the position of the reference axis/zero of the component with respect to external alignment references called fiducials: fiducialisation process. The mock-up was equipped with high precision Wire Position Sensors (WPS) and inclinometers – giving feedback data to compute the position of supporting structures w.r.t. reference coordinate system (linked to stretched wire). All tests were performed under the control of specially designed software to examine the system behaviour during repositioning and verify the operation of pre-alignment control algorithms.

Test Mock-up

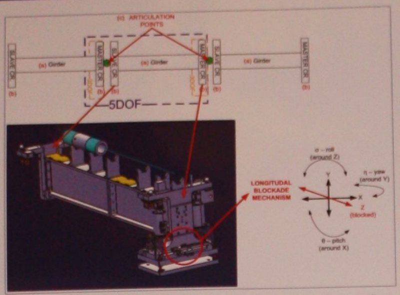
"Snake" type girders configuration

(a) Girders

All CLIC RF components will be installed on modular girders, which will be used as a support for their pre-alignment.

(b) Cradles

Each girder is equipped with two side interfaces called MASTER and SLAVE "cradle". Motorization is installed only on the MASTER cradle. The non-motorized SLAVE cradle is driven by the adjacent girder. This solution smooths out "naturally" the pre-alignment of adjacent girders.

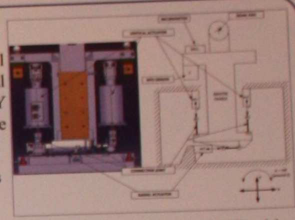


(c) Articulation points

MASTER-SLAVE connection quality plays a very important role in the "snake" type girder configuration. Interconnection offset error after pre-alignment should be lower than 10 µm rms.

MASTER cradle - 3 degrees of freedom

The cradle is suspended on two vertical actuators and is connected with one radial actuator. The actuators control the X-Y position as well as the roll of a cradle resulting in a 3 DOF mechanism.



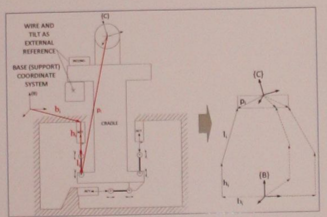
"Snake" type configuration - 5 degrees of freedom

Because longitudinal motion is blocked mechanically at the MASTER side, a combination of cradles MASTER-SLAVE-MASTER allows girder position control in 5 DOF. The whole "snake" structure can be pre-aligned by setting the beam axis positions of all MASTER cradles in one line w.r.t. reference axis coming from the tunnel coordinate system which shall be an external and independent reference for component alignment.

Control algorithms and technological limits

Master cradle kinematics – theoretical approach

The 3 DOF MASTER cradle, equipped with linear actuators, can be considered as an object in the 2D space. It forms a triple, parallel P-R-R (prismatic-rotation-rotation) kinematics circuit, defined by cradle vectors ($\mathbf{p}_i^C$) and base coordinates ($\mathbf{b}_i^B$, $\mathbf{h}_i^B$, $\mathbf{l}_i^B$). The cradle is suspended on joints (links) of constant length $\mathbf{l}_i$, and the joints are attached to the actuators of variable height $\mathbf{h}_i$. Inverse kinematics equations based on the vectors can give the wanted actuator lengths to reach requested cradle orientation (open-loop control).



Limits of open-loop control in the CLIC design

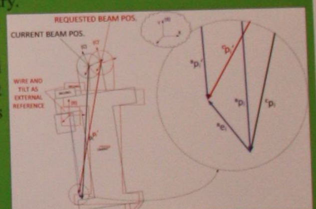
Inaccuracies of vector dimensions could result in errors during alignment. It will be impossible to link the actuator support coordinate system "rigidly" w.r.t. tunnel coordinate system in the CLIC design because of supporting system component's machining errors and nonlinearities, settling errors of supporting plates and assembly inaccuracies.

Practical approach – closed-loop control

Approximate relative movements of actuators ($\Delta h_{i\_vertical}$, Δh_{i_radial}) to reach required girder position can be calculated using shift error vectors. These vectors are based on sensor feedback data, on requested RF component's axis position and on fiducialised cradle/girder geometry.

Vector ${}^{B}\mathbf{p}_i$ defines the current position of the i[th] cradle suspension node in {**B**} and vector ${}^{B}\mathbf{p}_i'$ presents the requested position of the same node in {**B**}. Shift error vector for each suspension node is then ${}^{B}\mathbf{e}_i = {}^{B}\mathbf{p}_i' - {}^{B}\mathbf{p}_i$.

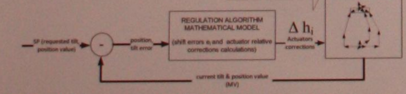
$$\Delta h_{i\_vertical} = f(e_i) = y_i$$
$$\Delta h_{i\_radial} = f(e_i) = x_i$$



Simulations and tests results

Algorithm implementation and tests

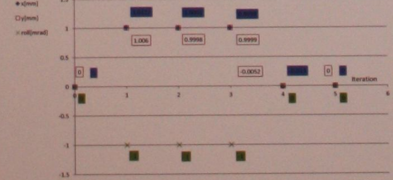
To verify algorithm performance, the mathematical model of control algorithm and MASTER cradle kinematics was created. The component innacuracies and nonlinearities were included in simulation. Cradle response for requested position change was verified.



In parallel, a series of similar tests was performed on a real mock-up. Two different cradle responses were observed.

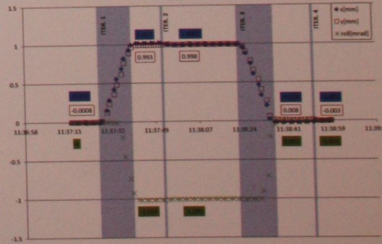
Simulated single step response

Simulations with different initial regulation positions showed that the algorithm is convergent in two regulation cycles for displacements ranges: [±1 mm ±1 mm ±1 mrad] with final position error lower than 1 µm.



Real MASTER cradle step response

The mock-up tests confirmed simulation results: for both tested cradles, the final position was achieved in two to maximum three regulation steps (within the sensor noise).



The WPS sensor noise was at the level of 5 μm_{p-p} and inclinometer noise at the level of 5 μrad_{p-p}

Maximal absolute value of requested position was overshot after the first iteration by less than 50 µm.

Conclusions

Closed loop regulation – so far only tested with relative displacements – exempt us from problems with cradle suspension component inaccuracies. There is also no significant effect of components nonlinearities and inaccuracies for the final algorithm iteration number. This was confirmed by the similar results observed for all the tested conditions.

MEDSI2012

7[th] International Conference on Mechanical Engineering Design of Synchrotron Radiation Equipment and Instrumentation • Shanghai, China • 15[th] – 19[th] October 2012

M. Sosin, M. Anastasopoulos, N. Chritin, S. Griffet, J. Kemppinen, H. Mainaud Durand, V. Rude

CERN, Geneva, Switzerland